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Impact of Integrated Nutrient Management Based on Silicon to Morpho-Physiological Changes on Maize: Enhancing Light Interception and Radiation use Efficiency

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Environmentally sustainable maize cultivation is essential to optimise its growth and yield potential for global food security as a key goal in sustainable agriculture. Integrated Nutrient Management (INM), when coupled with silicon (Si) supplementation, has gained attention for its potential to improve crop productivity. This study investigates the impact of INM practices enriched with silicon on maize morphology and physiology changes, with a particular focus on increasing light interception (f) and Plant solar energy conversion efficiency (P-SECE) or the commons term called RUE. Experiments were conducted during the wet season of December 2022 to March 2023 in Triguna Abadi Grower group's Field Trial Center, Sukorambi Village, Jember, East Java, Indonesia. Two corn varieties which one is hybrid (P5027) and the other open pollinated (Lamuru) were cultivated using conventional chemical fertilizer and combined with the sole of INM and Si as well as INM+Si under a split plot design. The results showed that INM+Si significantly changed the morpho-physiological characteristics of plants so that the canopy architecture was ideal for increasing light interception in the vegetative phase by up to 3,23% compared to conventional fertilisation. In general,the INM, Si, and INM+Si fertilization methods were able to increase interception and photosynthetic efficiency compared to conventional fertilization, which had a positive impact on P-SECE levels till 1,66-2,36% and plant growth which illustrated an increase in dry weight up to 47,45%. Meanwhile, P5027, which has a more ideal canopy architecture than Lamuru, has relatively better interception efficiency, P-SECE, and growth. Significant findings related to sustainable agriculture are that Si fertilisation has a better macro-nutrient balance illustrated by the N/P ratio at 8.75. The increase in interception efficiency, RUE, and macro-nutrient balance due to the INM with Si Based fertilisation method led to increased plant growth and yield that support food security.
Keyword: INM, Light interception, Maize, N/P ratio, Plant growth, RUE, Silicon, Sustainable Agriculture.

INTRODUCTION

Maize as an important food and feed commodity in Indonesia and globally still has gaps between productivity and yield potential, happened both at the farm level and research. Maize productivity currently reaches 5.7 Ton/Ha (BPS, 2021) from a potential yield of around 13.7 Ton/Ha for hybrids and 8.9 Ton/Ha for open pollination (Rahmi *et al.*, 2020). Maize research have productivity ranging from 7.96-11.68 Ton/Ha for hybrids and 4.3-6.63 Ton/Ha for composites (Karim *et al.*, 2020; Suryanto, 2018; Wahyudin *et al.*, 2017). Efforts to increase maize and other crop productivity have been made through various technical culture modifications such as the assembly of varieties (Molero *et al.*, 2019), nutrition (Hammad *et al.*, 2016), planting systems (Moroyoqui-Parra *et al.*, 2024), and other technical culture practices related to increase radiation use efficiency (RUE) by improved light interception. Light interception (f) and RUE have a significant influence on plant growth and yield. Studies have shown that increasing light interception can increase plant biomass and

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yield (Sinclair and Muchow, 1999). In addition, an increase in RUE can also increase the efficiency of solar energy utilisation by plants, which in turn can increase crop yield (Tao *et al.,* 2018). Therefore, it is important to pay attention to these two factors in an effort to increase agricultural productivity.

The main environmental factors that determine corn growth and yield include solar light and plant nutrients. Solar light especially light intensity is important for plants related by photosynthesis. Plant growth depends on the level of capture and absorption of solar energy and the efficiency of photosynthesis, so it is optimum to convert solar energy into chemical energy in the form of plant dry weight. Plant dry weight is an important component that determines yield which is built through the level of light interception by the canopy structure during plant growth (Lee and Tollenaar, 2007). Crop yield can be increased by improving light interception through variety selection, population density, and planting season (Morales-Ruiz *et al.,* 2016) as well as nutrient.

Light interception by plants is determined by the type of plant canopy architecture that is influenced by morphological characteristics such as leaf angle, leaf orientation value (LOV), plant height (PH), and LAI (Li *et al.,* 2018a). Smaller leaf angle (more upright), higher leaf orientation and plant height, as well as appropriate leaf structure and size can increase plant solar energy conversion efficiency (P-SECE) or the commons term called RUE due to increased interception, light distribution, and photosynthesis rate in plant leaves (Huang *et al.,* 2017; Xue *et al.,* 2015). Beside that, optimum LAI allows an increase in plant dry weight in line with the distribution of light and PAR that is more absorbed (Diaz, *et al.,* 2011). The relationship between canopy architecture and light interception is linked to LAI through Beer's Law exponential function (Maddonni *et al.,* 2001) thus involving the light extinction coefficient (k) to characterize light interception. The value of k, which represents interception efficiency, is inversely related to LAI and interception efficiency (f), especially in the middle and upper parts of the canopy (Flénet *et al.,* 1996; Li *et al.,* 2018a). Selection of maize varieties that have a canopy structure and *idiotype* favourable for optimum light interception, has the potential to increase light interception which has implications for increasing P-SECE values.

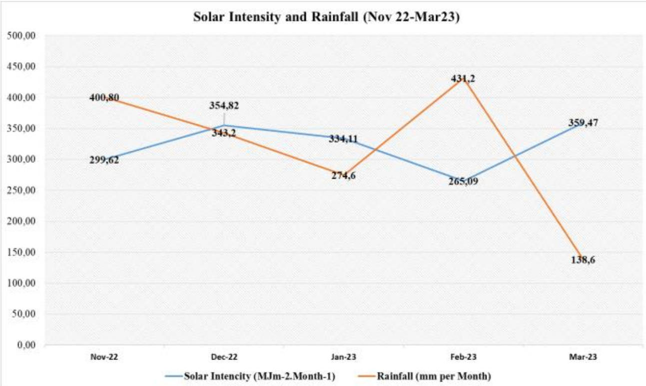
Plant canopy architecture can be modified through the application of INM (Integrated Nutrient Management) and beneficial nutrients such as silicon (Si). INM is a technique of providing inorganic and organic nutrients in sufficient and balanced amounts and combining them with specific microbes (Selim, 2020). The application of biofertilizers combined with inorganic and organic fertilizers significantly changed the morpho-physiology of mustard (*Brassica campestris*) plants, thereby increasing LAI, CGR, and NAR (Banerjee *et al.,* 2012). In addition, INM was also reported to increase chlorophyll content, proline, LAI, CGR, NAR, and HI of mustard plants with a combination of chemical fertilizers, biologicals, and vermicompost (Mondal *et al.,* 2017). Meanwhile, Si is one of the *beneficial* nutrients for gramineae plants (Neu *et al.,* 2017) which contributes to inducing enzymes related to photosynthesis so that it affects the rate of photosynthesis which has implications for growth rate and productivity (Oktarina *et al.,* 2021). The element silicon increases cell rigidity thereby reducing leaf angle and has implications for sunlight capture efficiency (Oktarina *et al.,* 2021; Vasanthi *et al.,* 2012). In addition, this element can increase N use efficiency (Neu *et al.,* 2017; Pulung, 2007; Soeroso *et al.,* 2021), increase P uptake (Neu *et al.,* 2017; Soeroso *et al.,* 2021; Syarifuddin, 2011) and translocation of the element in plant tissues (Husnain, 2011). The results of other studies, silicon can increase stomata conductance, and chlorophyll content (Arista and Wijaya, 2015; Yukamgo, 2007). Si-based INMs have the potential to affect plant morphology and physiology which has the opportunity to become one of the keys to improving light interception and P-SECE.

Research related with the efforts to increase the value of P-SECE in corn has been widely carried out, but there are still few that connect with nutrients, especially *beneficial* nutrients such as Si that have the potential to encourage improvements in plant morphology and physiology to increased interception and absorption of solar light. Plant productivity is determined by the ability of plants to capture, absorb and convert solar energy into biomass (Campillo, 2012). For this reason, efforts are needed to increase solar light interception and absorption through technical culture modifications that present the optimization of genetic and environmental potential through a variety selection and application of INM based on Si.

MATERIALS AND METHODS

***Experimental site*:** The field experiment was conducted in Triguna Abadi Grower group's Field Trial Center, Sukorambi Village, Jember, East Java, Indonesia with a latitude is 113º 39'.32" E and longitude is 8º 10'.44" S. The average altitude is about 134.4 m above the mean sea level as wet season from December 2022 to March 2023.

***Soil and Climatic Conditions*:** Soil analysis before planting indicated low available N (0.1%), very high available P and K (36.9 and 86 ppm), very low C-organic (0.96%), low C/N ratio (9.6), very low pH 5.3 (H_2O) and 4,2 (KCl), soil texture classified as clay loam with 21% sand, 46% silt, and 33% clay, available Si 228 ppm (low), low SiO_2 (silica) 63.21%, and medium of cation exchange capacity (20.38 cmol. Kg^{-1}). The average rainfall per month during the growing season is 317,68 mm. $Month^{-1}$ (high) with a solar radiation intensity of 322,62 $MJ.m^{-2}Month^{-1}$ equivalent to 254.49 $Cal.cm^{-2}.Day^{1}$ (medium-low) (Fig. 1). Minimum and maximum temperature around 21-34°C with high relative humidity around 86-89%.



Source: Soil Department of Agriculture Faculty of Jember University

Figure 1. Solar Intensity and Rainfall during Research conducted.

***Experimental Design and Treatment*:** The experiment was laid out in a split plot design with variety as the main plot and a kind of fertilizer method as a subplot. The main plot consisted of V1= P5027 Hybrid and V2= Lamuru Composite, while the subplots consisted of S0= (Control/Conventional Fertilization), S1= INM Fertilization Method, S2= Si Fertilization, and S3= INM+Si Fertilization. The treatment combination consisted of 8 treatment combinations that were repeated 4 times so that there were 32 experimental units. The size of the experimental plot was 3.2x2.5m which was made with a bed system with a bed height of 30 cm. Plant spacing used *double row* (80+40) x 20 cm with the distance between experimental plots was 75 cm and the distance between replicates was 150 cm. The number of plants per experimental plot was 72 plants with a density of 8.3 plants/m2.

***Material and Crop Establishment*:** The experimental materials consisted of 2 maize varieties: hybrid and composite (open pollination) and fertilizer types: inorganic, organic, and biofertilizer. The hybrid variety is represented by P5027, which is characterized by a narrow leaf angle and high yield potential, while the composite variety is Lamuru, characterized by a semi-horizontal leaf angle and medium-low yield potential. Inorganic fertilizers contain N, P, and K elements (Urea, SP36, KCl, ZA, and NPK compound fertilizers) with recommended doses of 200Kg.Ha^{-1} N, 100Kg.Ha^{-1} P_2O5, and 80Kg.Ha^{-1} K2O (based on the results of soil analysis and *best practices of* local farmers) with the application of fertilizer types in the form of Urea 200Kg.Ha^{-1}, Za 300 Kg.Ha^{-1}, Compound Fertilizer (N:P: K 15:15:15) Phonska 300 Kg.Ha^{-1}, SP36 152.8 Kg.Ha^{-1}, and KCl 58.3 Kg.Ha^{-1}. INM (*Integrated Nutrient Management)* materials consist of Bokashi (cow dung and other materials), Biofertilizer containing Bacillus sp, Aspergillus sp, Lactobacillus sp, Pseudomonas sp, and other beneficial bacteria (eco enzymes). Silicon fertilizer consists of solid and liquid 90% inorganic fertilizer (SiO2) and organic Si fertilizer in the form of husk ash (brick burning waste), corn plant ash, and bamboo leaf ash. Application of inorganic fertilizers 4x throughout plant growth for all plots, namely at planting (basic fertilization) consisting of SP36 (100%), KCl (100%), and Phonska (25%). first application is Urea, ZA, and Phonska each 25% of the total 10 days after planting (DAP), followed by 50% Urea, 25% ZA, and 50% Phonska as 20 DAP. The last inorganic application was 30 DAP with 25% Urea and 50% ZA. Solid organic fertilizer made from cow dung was applied 7 days before planting for INM treatment plots at a dose of 7.5 T.ha^{-1} and mixed solid organic fertilizer of cow dung and corn stalks (7.5T.Ha^{-1}), rice husk charcoal and ash each 0.25 T.ha^{-1}, and corn and bamboo ash each 0.5 T.ha^{-1} for INM+Si plots. Liquid organic fertilizer consisted of blaze natura (macro and micronutrients), rabbit urine (Anbagenic), and other liquid organic handmade product each 100ml/15l water applied 8x from 10-50 DAP for INM and INM+Si plots. Biofertilizers consisted of several solid (Mustika Tani, Mycovir, and PGPR) and liquid (Kampeser, EM4, PGPR, and Triko) biofertilizer products, which all contained Lactobacillus sp, Pseudomonas sp, Aspergillus sp, Bacillus sp, Trichoderma sp, Rhizobium sp, Azotobacter sp, Actinomycetes sp, Mycoriza, Rhizobium, decomposing bacteria and other growth promoters. The biofertilizer was applied to INM and INM+Si plots with a frequency of 4x between 10-35 DAP. Inorganic Si fertilizer applied for Si and INM+Si treatment consisted of Sicarbon 60% SiO2 (10Kg.Ha^{-1}) and Susi 30% SiO2 (20 Kg.Ha^{-1}) applied through the roots at 10 DAP and 10-20-30 DAP. While inorganic Si applied with foliar consists of Silica 99.8% (Tanisil), NanoSilica 99.8% (Silfer), silica 90% (Maxil), 14% SiO2 and K 8% (Bensil+) frequency 3-8x between 10-50 DAP.

Land preparation was done by complete tillage with plots according to the treatment of each experiment. Randomization of plots according to the *split plot* experimental design procedure with the *main plot* randomized in a group randomized design. Planting was done with 2 seeds per hole with *double row* spacing. Thinning was done at 10 DAP so that there was 1 normal plant per planting hole. Maintenance includes fertilization according to the treatment, pest, and disease control is carried out if it exceeds the economic threshold of a 5% attack rate. Watering is done as needed and follows a direction that does not affect the treatment.

***Observation variable*:** The observation variables on morpho-physiology traits include plant height (PH), leaf angle, leaf orientation value (LOV), leaf area index (LAI), chlorophyll content, active stomata, crop growth rate (CGR), Net Assimilation Rate (NAR), Specific Leaf Area (SLA), Photosynthetic Yield (Fw/Fv), and dry weight matter. The observation variables for nutrition include Si, N, and P content in leaf tissue and rate of absorption. The effect of variety treatment and fertilization systems on light distribution in plants was determined by measuring

interception efficiency (f), light extinction coefficient (k), and P-SECE/RUE.

PH was determined by measuring the plant from the base of the rootstock to the top of the tassel (Liu *et al.*, 2017). Leaf angle was measured on leaves 1 and 3 (from top) during the vegetative stage and 2 and 4 leaves during the generative stage with a digital angle meter calibrated with a manual arc ruler. LOV was determined using the formula: LOV **= (90-a) x h/I**, where a is the leaf angle, h is the distance from the leaf base to the leaf apex, and l is the leaf length (Pepper *et al.*, 1977). The LAI value is obtained by dividing the leaf area (LA) by the unit area of land (GA) shaded by the canopy (Sitompul, 2016) which is formulated by: **LAI =** LA/GA where LAI = Leaf area index; LA = Leaf area (cm^2); GA = Shaded ground area. Leaf area is determined by the length times width method with the determination of constants through the results of leaf area meter measurements. Chlorophyll content was measured at the vegetative peak using a Soil Plant Analysis Development (SPAD) chlorophyll meter and extracted pigments were analysed using a spectrophotometer. Fresh corn leaves were pulverized and dissolved with 5ml of 80% acetone and filtered with filter paper. Subsequently, measurements were taken using a spectrophotometer at wavelengths of 645nm and 663nm. Active stomata was done by isolating leaf stomata using clear cut and isolation when 10-12 Am. Stomata isolation was placed on a microscope and then calculated using ImageJ software tools. CGR describes the total dry weight gain (W) of plants per unit time (t) per unit area of land (GA) formulated by **CGR = w2-w1/(t2-t1)*GA (**Sugito, 2013). Net Assimilation Rate (NAR) shows the rate of increase in plant dry weight per unit leaf area as a measure of photosynthetic efficiency (Sugito, 2013). NAR can be calculated with the formula: **NAR = W2-W1 x ln LA2-ln LA1(g.cm^{-2}.day^{-1})**
(LA2-LA1) (t2-t1)
Where, W1 = initial plant weight, W2 = final plant dry weight, LA1 = initial leaf area, LA2 = final leaf area, t1 = initial data collection time, and t2 = final data collection time. SLA is calculated with the quotient of leaf area (LA) with leaf dry weight (LW) formulated as SLA= LA/LW. Photosynthetic yield (Fv/Fm) was determined with the Mini-PAM Photosynthetic Yield analyzer through the Fv/Fm (Fluorescence) number during the vegetative peak. Dry weight matter was measured by weighing the dry weight of plants that were oven-dried for 2 days at 90°C and had a stable weight. Si content of leaf tissue was determined by gravimetric method, N content by Kjeldahl, and P using HNO3 Total. The level of uptake of each nutrition is calculated by multiplying the concentration of plant nutrient content with plant dry weight. The interception efficiency (f) was calculated by **f = (Ij-Il)/Ij x 100%**, where solar radiation above the canopy (Ij) and radiation that escapes below the canopy (Il). k is the conversion of the exponential function of radiation falling above the canopy (Ij) with radiation escaping under the plant canopy (Il) divided by LAI (Maddonni *et al*, 2001) which is formulated as follows: **k = -ln (Ij/Il)/LAI,** Plant Solar Energy Conversion Efficiency calculated with **P-SECE =** $\frac{\Delta W.K}{I.t.PAR}$ **x100%,** where ΔW: Difference in plant dry weight (g) per m^2 at one time period (t), K: Coefficient heat of combustion (4,000 cal.g^{-1}), I: Daily solar radiation intensity (cal.m^2 .day^{-1}), t: specific time period (days), PAR: *Photosynthetic Active Radiation* (0.45). Sunlight intensity above the canopy, light transmission, and reflection were measured with a Solarimeter.

***Data Analysis*:** Data were analyzed using *Analysis of Variance* (ANOVA) and Duncan's Multiple Range Test (DMRT) with a 95% confidence level if there were *significantly different* treatments. In addition, correlation analysis and *Principal Component Analysis* (PCA) were conducted to determine the relationship between treatments on the observation variables. The *tools* used for the overall data analysis were a combination of Excel 2019, SmartstatXL, XLSTAT 2018 and 2023, and SPSS 16.0.

RESULTS

Crop Morpho-Physiology Attributes

***Plant Height, Leaf angle, LOV, LAI, and k*:** The application of the INM fertilization method in combination with Si significantly changed the main morphological characteristics that make up the canopy architecture in the vegetative phase. INM+Si significantly increased plant height (25,6%) and LAI (43,96%), and decreased leaf angle (10,5%) and extinction coefficient (k) (27,9%) during the vegetative stage compare with conventional, and was not significantly different from the other methods in the generative stage (Table 1). LOV tended to increase for INM+Si during the vegetative stage at 78.04 and the Si fertilization method tended to be higher during the generative stage at 85.04 (Fig.2). The independent effect of variety on canopy structure showed P5027 significantly had lower plant height, leaf angle, and k during the vegetative stage and LAI as well as LOV tended to be higher than Lamuru.

***Chlorophyll content, Active stomata, and Yield Photosynthetic*:** Chlorophyll content was not significantly different for all treatment combinations and their interactions, but P5027 and Si treatments tended to be higher by SPAD measurement at 56.7 and 56.4 spp units, respectively (Table 2). Similar results were related to chlorophyll content by spectrophotometer where P5027 and Si fertilization contained the most chlorophyll each 47.76 and 48.87 mg.ml^{-1} (Fig.3a). The chlorophyll a/b ratio in this study showed that INM+Si fertilization was significantly highest and tended to be higher for Lamuru (Fig.3b). The number of stomata of INM and INM+Si tends to be more than control and Si, while Lamuru significantly has more active stomata than P5027. However, the results of the current study showed that the

Table 1. Analysis of variance of morphological characteristics of the main plants that make up the plant canopy architecture.

Treatment	Morphology Attributes											
	Plant Height (cm)			Leaf Angle (°)			Leaf Area Index (LAI)			K		
	35 DAP	45 DAP	60 DAP	35 DAP	45 DAP	60 DAP	35 DAP	45 DAP	60 DAP	35 DAP	45 DAP	60 DAP
Variety												
P5027	99,85a	201,28a	260,14a	19,88a	15,63a	23,76a	1,28a	5,24a	6,93a	1,27a	0,35a	0,28a
Lamuru	112,64b	218,26b	259,63a	21,84b	19,40b	25,68a	1,47a	4,97a	6,25a	1,06a	0,36a	0,30a
Duncan 5%	2.27	2.40	ns	0.30	0.43	ns	ns	ns	ns	ns	ns	ns
CV (%)	8.54	4.57	17.12	5.77	9.85	15.92	32.78	9.27	12.66	50.97	6.87	15.57
Fertilizer Methods												
Conventional	96,05a	189,38a	266,43a	21,15a	18,38a	22,91a	1,21a	4,14a	6,52a	1,35a	0,43a	0,29a
INM	103,99a	213,78b	258,19a	20,78a	17,37a	24,44a	1,38a	5,10b	6,75a	1,15a	0,35b	0,30a
Si	104,30a	206,35b	249,41a	21,03a	17,70a	25,39a	1,33a	5,21b	6,56a	1,12a	0,34bc	0,29a
INM+Si	120,65b	229,58c	265,53a	20,47a	16,63a	26,14a	1,56a	5,96c	6,51a	1,03a	0,31c	0,29a
Duncan 5%	3.00	4.40	ns	ns	ns	ns	ns	0.17	ns	ns	0.03	ns
CV (%)	8.08	5.94	11.91	9.13	8.50	12.43	24.60	9.30	12.15	32.45	5.57	9.33

Noted: Columns with the same letter in each factor indicated equal as DMRT 5%; CV= coefficient of variation; DAP= Day after planting; k= Extinction Coeficient

photosynthetic efficiency and results were not significantly different for all treatments with Lamuru and INM+Si tending to be higher with Fv/Fm of 0.29 and 0.30 (Table 2).

Table 2. Impact of some fertilizer methods on physiological characteristics of hybrid and composite maize.

Treatment	Physiology Attributes		
	Chlorophyll SPAD (Unit spp)	Active Stomata (unit)	Yield Photosynthetic (Fw/Fv)
	50 DAP	50 DAP	50 DAP
Variety			
P5027	56,57 a	110,81a	0,27 a
Lamuru	53,42 a	126,62b	0,29 a
Duncan 5%	ns	2,60	ns
CV (%)	8,82	8,81	23,87
Fertilizer Methods			
Conventional	54,44 a	113,87a	0,29 a
INM	54,16 a	123,25a	0,27 a
Si	56,54 a	113,87a	0,28 a
INM+Si	54,84 a	123,87a	0,30 a
Duncan 5%	ns	ns	ns
CV (%)	6,76	15,44	22,77

Noted: Columns with the same letter in each factor indicated equal as DMRT 5%; CV= coefficient of variation; DAP= Day after pl

Table 3. CGR, SLA, and dry weight of vegetative and generative phase.

Treatment	Physiology Attributes								
	Crop Growth Rate ($g.m^{-2}.day^{-1}$)			Spesific Leaf Area ($cm^2.g^{-1}$)			Dry Weight Matter (g)		
	45 DAP	60 DAP	100 DAP	35 DAP	45 DAP	60 DAP	35 DAP	45 DAP	60 DAP
Variety									
P5027	65,09 a	36,62 a	57,25 a	74,06 a	117,38 b	168,85 b	32,13 a	101,78 a	180,14 a
Lamuru	64,75 a	34,35 a	55,05 a	69,85 a	99,54 a	147,50 a	36,78 a	106,07 a	179,57 a
Duncan 5%	ns	ns	ns	ns	1,00	3,96	ns	ns	ns
CV (%)	13,89	26,59	11,71	22,86	3,69	10,04	18,03	3,98	11,83
Fertilizer Methods									
Conventional	48,40 a	47,18 c	46,37 a	74,24 a	103,23 a	160,41 a	28,63 a	80,42 a	181,39 a
INM	70,08 b	31,54 ab	62,69 a	74,84 a	109,25 a	164,69 a	32,31 a	107,30 b	174,78 a
Si	68,85 b	38,57 bc	58,02 a	70,81 a	109,09 a	149,97 a	35,73 ab	109,40 b	191,93 a
INM+Si	72,37 b	24,64 a	57,52 a	67,94 a	112,27 a	157,64 a	41,14 b	118,58 b	171,31 a
Duncan 5%	5,80	4,04	ns	ns	ns	ns	2,68	5,40	ns
CV (%)	25,41	32,23	27,57	17,19	7,90	9,06	22,01	14,73	11,39

Noted: Columns with the same letter in each factor indicated equal as DMRT 5%; CV= coefficient of variation; DAP= Day after planting

CGR, NAR, SLA, and Dry Weight Matter**:** The results showed that the CGR of corn applied with INM, SI, and INM+Si was significantly higher than the control each in order 44,8%, 42,3%, and 49,5% (Table 3) during the vegetative phase. However, in the generative phase, the control had a very significantly higher CGR than INM, Si, and INM+Si each in order 49,6%, 22,3%, and 91,5%. SLA was not significantly different in fertilization methods with INM+Si relatively lowest at 35 DAP, control tended to be lowest at 45 DAP, and Si relatively lowest during generative. However, Lamuru which has a lower SLA than P5027 was not significantly different for CGR and plant dry weight. NAR as an indicator of photosynthetic efficiency showed no significant difference for all treatments in the vegetative phase with a tendency for INM and P5027 to be higher (Figure 5a), while the control was the highest in the generative phase followed by Si (Figure 5b). As a result, the CGR of the control at the generative stage was the highest not different with Si treatment but dry weight tended to be higher after Si treatment although not significantly different statistically.

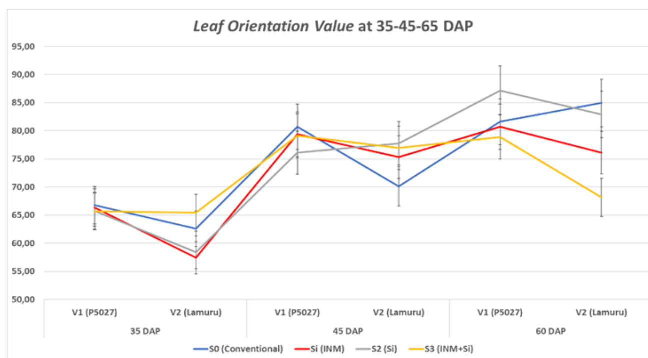
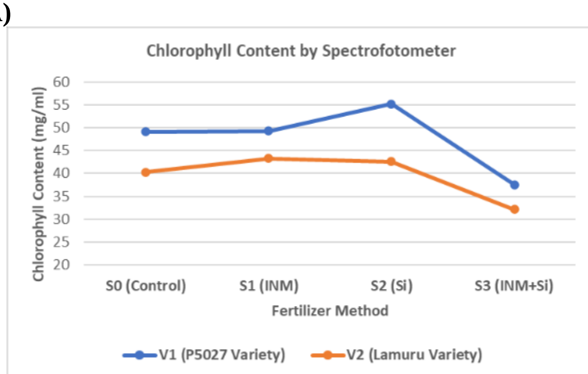


Figure 2. LOV of maize plants with several fertilization methods during vegetative and generative stages.

Si, N, P content in leaf tissue and absorption rate of Si, N, and P**:** Si, N, and P contents in leaf tissues showed no significant difference for all treatments and their interaction with Lamuru and INM+Si were relatively higher for Si

content at 6.76% and 6.83%, respectively (Figure 6a). While N content of INM and P5027 treatments was relatively higher at 2.57% and 2.42% (Figure 6b), and P content showed Lamuru and conventional fertilization tended to be higher at 0.32% and 0.34% (Figure 6c). Plant growth and yield are determined by the balance of N, P, and K nutrients that can be calculated by the DRIS method.

(A)



(B)

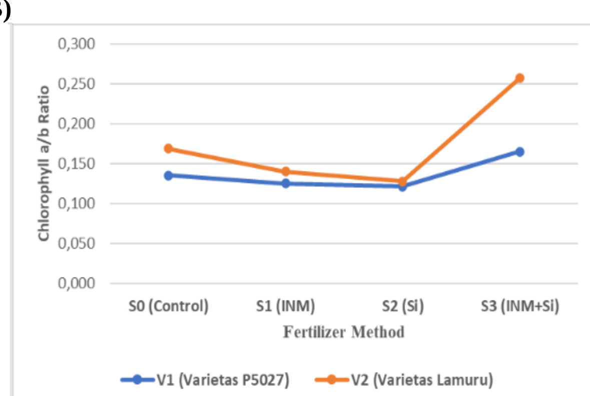


Figure 3. Chlorophyll content by spectrophotometer method (A) and chlorophyll a/b ratio (B).

The optimum N/P ratio to obtain the most balanced macronutrients associated with the highest corn production is 8.9 (Saputra, 2007). The N/P ratios of the conventional fertilization method, INM, Si, and INM+Si were 7.58; 7.9; 8.75; and 6.36, respectively, while P5027 was relatively higher than Lamuru at 7.92 (Figure 6d).

The Si, N, and P uptake levels of the varieties were not significantly different, but N uptake was significantly higher for INM and Si methods as well and P uptake was higher for INM and INM+Si fertilization relatively. While Si uptake was not different for all treatments with INM and Si as well as INM+Si tended to be higher than the conventional method (Table 4). The relationship of Si, N, and P uptake levels to the main components of plant canopy architecture such as leaf angle, plant height, LOV, ILD, and SLA showed that the level of Si uptake was significantly positively correlated with plant height, LAI and negatively correlated with SLA values (Table 5).

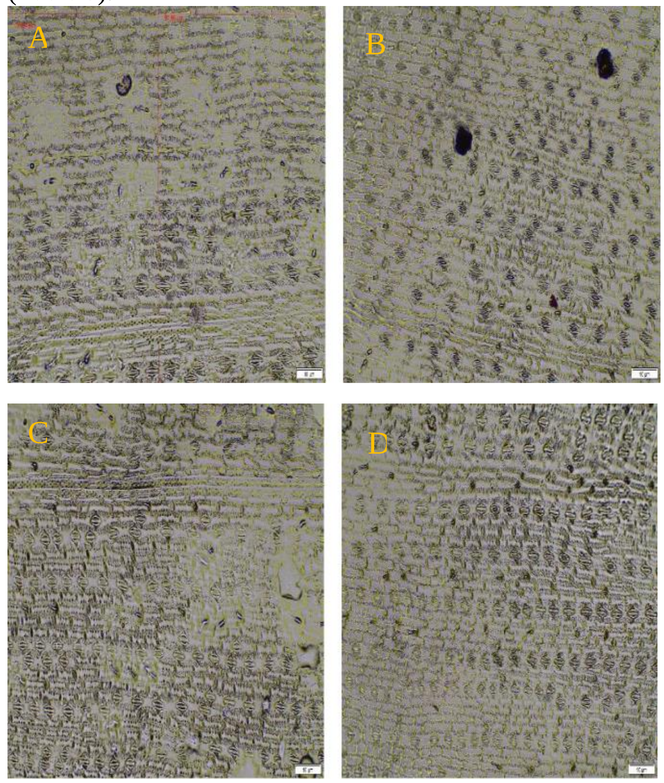


Figure 4. Stomata number: A. Lamuru Vs Control; B. Lamuru Vs INM; C. Lamuru Vs Si; D. Lamuru Vs INM+Si .

In addition, Si uptake was also significantly positively correlated with N and P uptake with determination coefficients of 54.6% and 59.9%. Meanwhile, N uptake was significantly correlated with LOV, and the level of P uptake was positively related to plant height and negatively correlated with SLA. The relationship between the level of Si uptake with CGR, dry weight, and P-SECE showed a very significant positive linear relationship of 91.8%, 96.9%, and 96,9%, respectively, where the effect of Si on CGR reached 84.3%, 93.9% on plant dry weight and influenced P-SECE 95 HST by 93.8% (Table 6).

Table 4. Rate of Si, N, and P Absorption of some varieties with different fertilizer methods.

Treatment	Absorption Rate of Si, N, and P		
	Si	N	P
	75 DAP	75 DAP	75 DAP
Variety			
P5027	27,05 ± 1,96 a	10,03 ± 0,75 a	1,28 ± 0,11 a
Lamuru	27,35 ± 2,19 a	9,70 ± 1,16 a	1,31 ± 0,11 a
Fertilizer Methods			
Conventional	24,49 ± 2,63 a	9,49 ± 1,03 ab	1,25 ± 0,14 a
INM	28,53 ± 3,93 a	11,00 ± 1,47 b	1,39 ± 0,19 a
Si	28,15 ± 3,33 a	10,67 ± 1,31 b	1,23 ± 0,19 a
INM+Si	27,62 ± 2,04 a	8,30 ± 1,28 a	1,30 ± 0,16 a

Noted: Columns with the same letter in each factor indicated equal as DMRT 5%; CV= coefficient of variation; DAP= Day after planting

Table 5. Correlation of Si, N, and P Absorption Rate with Morphology Changes

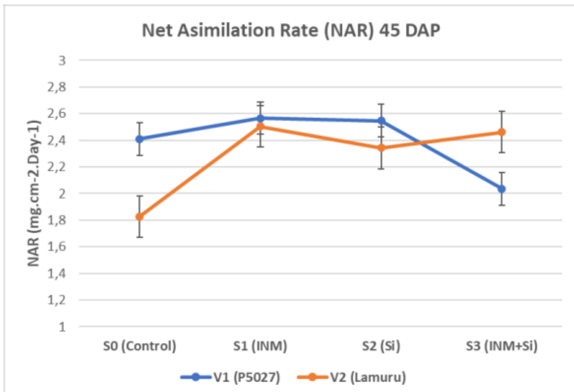
Variables	N Absorp(g)	P Absorp(g)	Si Absorp(g)	LA 65 DAP	LOV 65 DAP	SLA 65 DAP	PH 45 DAP	LAI 45 DAP
N Absorption rate(g)	1	0,782	0,739	-0,076	0,503	-0,245	0,049	-0,0002
P Absorption rate(g)	0,782	1	0,774	0,037	0,271	-0,332	0,374	0,185
Si Absorption rate(g)	0,739	0,774	1	0,169	0,267	-0,320	0,456	0,331

Coefficients of determination (Pearson):

Variables	N Absorp(g)	P Absorp(g)	Si Absorp(g)	LA 65 DAP	LOV 65 DAP	SLA 65 DAP	PH 45 DAP	LAI 45 DAP
N Absorption rate(g)	1	0,612	0,546	0,006	0,253	0,060	0,002	0,000
P Absorption rate(g)	0,612	1	0,599	0,001	0,073	0,110	0,140	0,034
Si Absorption rate(g)	0,546	0,599	1	0,029	0,071	0,102	0,208	0,109

Noted: N= Nitrogen; P= Phospor; Si= Silicon; LA= Leaf angle; LOV= Leaf Orientation Value; SLA= Spesific Leaf Area; PH= Plant Height; LAI= Leaf Area Index; g= gram; DAP= Day after planting

(A)



(B)

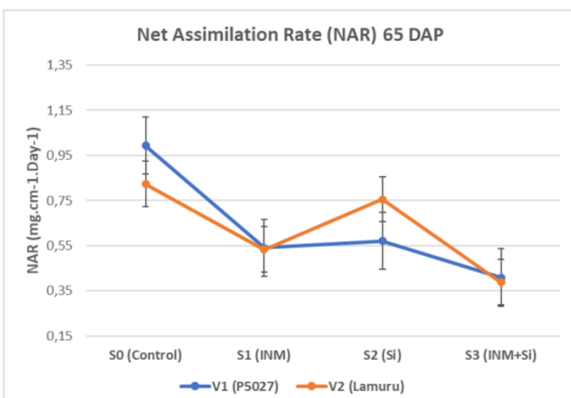
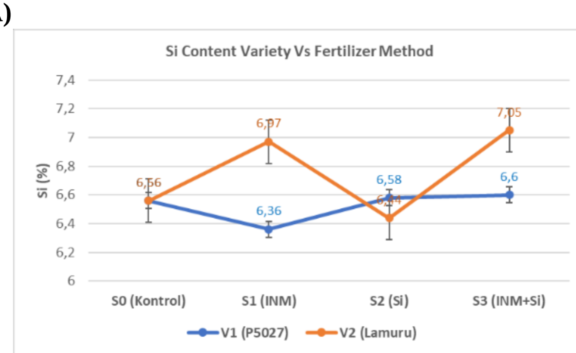


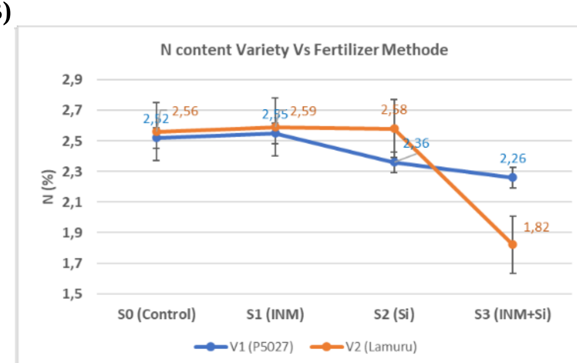
Figure 5. NAR during vegetative stage (A) and NAR during generative stage (B).

***Light Interception and Solar Energy Conversion Efficiency*:** The interception efficiency (f) was only significantly different among fertilization treatments at the beginning of the vegetative stage at 35 DAP where INM+Si was the highest at 78.02%. Subsequent growth stages were not significantly different, but all fertilization methods were relatively higher than conventional especially INM+Si which reached 89.54% at 95 DAP (Table 7). Meanwhile, varieties interception efficiency showed that P5027 was significantly higher during the generative stage at 86.45%.

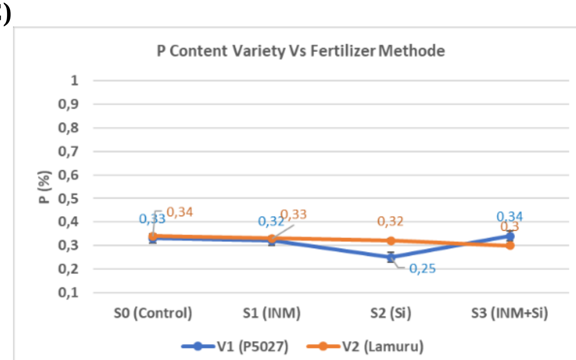
(A)



(B)



(C)



(D)

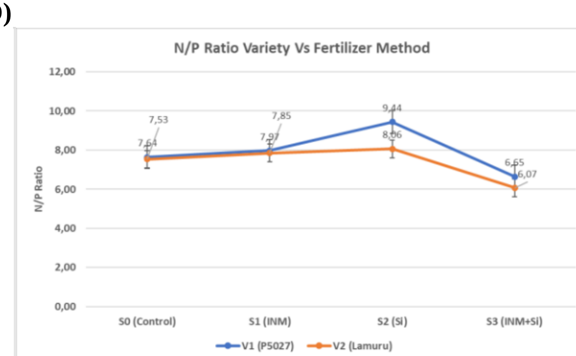


Figure 6. Leaf Si content (A), N (B), P (C), and N/P ratio of maize leaves 75 DAP (D).

The level of interception has implications for plant solar energy conversion efficiency (P-SECE) where INM+Si is the

highest during vegetative time at 7.35%, not significantly different from Si (6.78%) and INM (6.65%) but significant higher than conventional's P-SECE is only 4.99%. Furthermore, P-SECE was not significantly different during the generative stage, but all treatments were relatively higher than control/conventional fertilization at the end of growth. The difference in P-SECE of INM, SI, and INM+Si compared to conventional was 1.64%, 1.63%, and 0.95%, respectively. The P-SECE of varieties showed no significant difference with Lamuru relatively higher during vegetative time and P5027 tended to be higher before harvest.

Table 6. Relationship of Si uptake rate with plant growth and P-SECE.

Correlation matrix (Pearson):

Variables	Si Absorption Rate (g/Plant)
Si Absorption	1
CGR100	0,918
CGR65	-0,128
CGR45	0,164
W100	0,969
W65	0,175
W45	0,349
P-SECE 95	0,969
P-SECE 65	0,175
P-SECE 45	0,349

Coefficients of determination (Pearson):

Variables	Si Absorption Rate (g/Plant)
Si Absorption	1
CGR100	0,843
CGR65	0,016
CGR45	0,027
W100	0,939
W65	0,031
W45	0,122
P-SECE 95	0,938
P-SECE 65	0,031
P-SECE 45	0,122

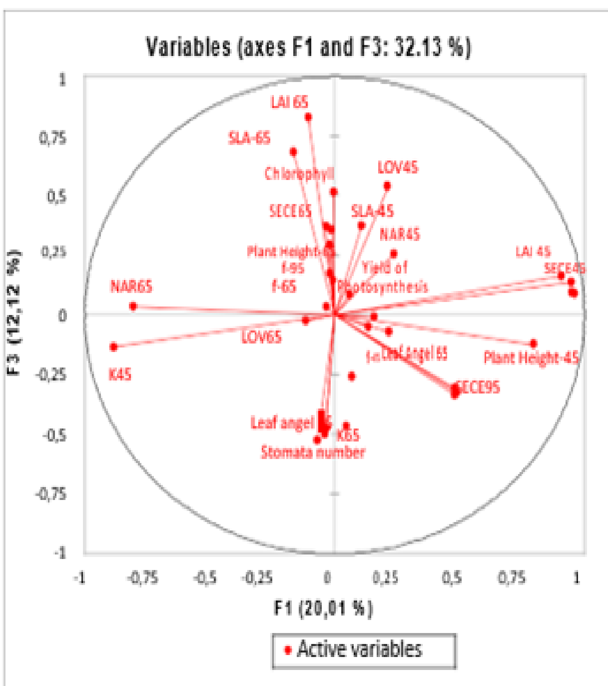


Figure 7. Relationship between P-SECE, f, and morpho-physiology of maize plants.

Table 7. Effects of variety and fertilization method on interception efficiency and solar energy conversion efficiency.

Treatment	Light Interception Efficiency (f) and Solar Energy Conversion Efficiency (P-SECE)							
	f (%)				SECE (%)			
	35 DAP	45 DAP	60 DAP	95 DAP	35 DAP	45 DAP	60 DAP	95 DAP
Variety								
P5027	75,36 a	82,75 a	86,45 b	89,52 a	2,56 a	6,31 a	8,13 a	11,90 a
Lamuru	76,43 a	82,78 a	84,62 a	88,83 a	3,05 a	6,58 a	8,11 a	11,63 a
Duncan 5%	ns	ns	0,3	ns	ns	ns	ns	ns
CV (%)	3,55	2,55	1,45	1,51	24,79	3,98	11,83	6,82
Fertilizer Methods								
Conventional	74,79 ab	81,71 a	85,19 a	88,66 a	2,53 a	4,99 a	8,19 a	10,71 a
INM	76,32 bc	83,23 a	85,79 a	89,14 a	2,64 a	6,65 b	7,89 a	12,35 a
Si	74,47 a	82,22 a	85,29 a	89,36 a	2,75 a	6,78 b	8,67 a	12,34 a
INM+Si	78,02 c	83,90 a	85,87 a	89,54 a	3,30 a	7,35 b	7,73 a	11,66 a
Duncan 5%	0,59	ns	ns	ns	ns	0,34	ns	ns
CV (%)	2,19	2,03	1,57	1,08	22,83	14,73	11,39	14,54

Noted: Columns with the same letter in each factor indicated equal as DMRT 5%; CV= coefficient of variation; DAP= Day a

DISCUSSION

The results of previous studies showed that plant height increased in INM fertilization in the form of Humic acid (Filho *et al.,* 2020), the use of biofertilizers increased the height of potato (Solanum tuberosum L.), tomato, maize (Bhattacharyya and Jha, 2012), tobacco (Zhang and Kong, 2014) and wheat (Afzal and Bano, 2008). In addition to INM, the nutrient Si was also reported to increase plant height (Syahri *et al.,* 2016) quadratically with increasing Si intake (Elawad, *et al.,* 1982). Previous research showed similar conditions related to LAI, where changes in canopy structure caused by INM application increased LAI in the vegetative phase and decreased during generative (Banerjee *et al.,* 2012; Mondal *et al.,* 2017) and LAI increased in all phases of mustard growth (Banerjee *et al.,* 2011). The results of research by Sinha *et al.,* 2003 showed that the addition of N had no effect on plant height, but affected LAI, dry weight, and CGR. The increase in LAI when vegetative in the current study was followed by a decrease in k, this is in accordance with Beer's law which states that LAI has an exponential function with a light interception (Maddonni *et al.,* 2001) and correlates with k which decreases with increasing LAI (Li *et al.,* 2018b).

Our Result show that the lower leaf angle in the INM+Si application as vegetative phase was related to the Si content in the leaf tissue which was relatively higher than the other treatments (Figure 5a). The increased Si content in the leaves has an impact on decreasing the leaf angle, thus affecting light interception (Oktarina *et al.,* 2021; Vasanthi *et al.,* 2012). The presence of significantly higher of plant height and LAI, smaller angle relatively, LOV tends to be larger, and k is significantly smaller in the INM+Si treatment in the vegetative phase caused an increase in interception efficiency between 78.02-83.9%, which is higher than other treatments (Table 7). The higher plant height allowed for increasing light interception efficiency (Li *et al.,* 2018b). More upright leaves can increase the even distribution of light and photosynthetic efficiency by 40% (Long *et al.,* 2006). In contrast to leaf

angle, higher LOV has a positive effect on light distribution. However, smaller angles and higher LOV do not necessarily increase crop productivity (Liu *et al.,* 2017).

The total chlorophyll content and ratio of chlorophyll a and b determine photosynthetic result and efficiency (Fv/Fm) where the higher chlorophyll content and chlorophyll a/b ratio will increase the result and photosynthetic efficiency (Sholikhah *et al.,* 2015; Yustiningsih, 2019). In addition to chlorophyll content, the number of active stomata also determines for results and efficiency of photosynthesis related to the amount of CO2 entering the leaves. P5027 and Si fertilization have chlorophyll content tend to be higher but INM+Si and Lamuru higher for chlorophyll a/b ratio and number of active stomata which implicated to be higher for Fv/Fm both of them. The nutrient Si stimulated protein and chlorophyll synthesis in the mesophyll (Tisdale *et al.,* 1985) and it was proven that increasing Si content in maize tissues increased chlorophyll content (Dimkpa *et al.,* 2012). Chlorophyll content also increased with INM treatment compared to control for mustard in previous studies (Mondal *et al.,* 2017), in potatoes (Selim *et al.,* 2012), and in corn (Abdelraouf *et al.,* 2013; Azab, 2016). However, there are research results that show chlorophyll content does not differ between control and INM (Filho *et al.,* 2020).

CGR is one of the plant growth indicator variables related to dry matter production. Based on data, this condition is in line with the vegetative phase of the plant dry weight where the control was significantly lower than the other treatments, but in generative dry weight was not significantly different for all treatments with Si and control tending to be higher. The vegetative CGR pattern is similar to LAI which is significantly higher than the control with INM+Si tending to be higher. This is related to the level of interception where increased LAI will increase light interception so that CGR also increases which will ultimately increase yield (Datta *et al.,* 2012). Meanwhile, CGR and dry weight among the varieties tried were not statistically significantly different. SLA shows the level of leaf thickness which is related to the level of light transmission and the thickness of palisade tissue. The smaller of SLA value, the thicker the leaf, which will reduce light transmission (Sugito, 2012) and increase palisade thickness to increase photosynthetic capacity (Utami, 2018). The lower SLA of INM+Si during vegetative time caused an increase in CGR, photosynthetic results, and plant dry weight. Meanwhile, the relatively low SLA Si treatment during the generative phase resulted in an increase in CGR and plant dry weight.

The current result show that Si fertilization methods and P5027 relatively have a better macronutrient balance than other treatments which will positively affect the physiological characteristics of plants including photosynthesis relatively. This is shown by Si fertilization which has relatively high chlorophyll content, high CGR and dry matter during vegetative and generative stages, relatively low SLA, and high NAR during the generative stage. While P5027 has a higher chlorophyll content and NAR relatively during vegetative.

The INM+Si fertilization method has implications for canopy architecture that is favorable to light distribution such as increasing plant height, LAI, and LOV and decreasing leaf angle and k in the vegetative phase. This increased light interception, which positively affected physiological characteristics such as the tendency to increase the chlorophyll a/b ratio, number of stomata, photo-synthesis yield, CGR, and dry weight in the vegetative phase. This condition is thought to be the effect of the role of Si that affects changes in plant morpho-physiological characteristics. The Si uptake rate of INM+Si, INM, and Si fertilization methods that were relatively higher than conventional fertilization was proportional to the interception rate and P-SECE.

The results of PCA analysis showed that photosynthetic results and efficiency were related to plant height, LAI, SLA, LOV, NAR, f, and P-SECE. This means that plant morphological characteristics such as plant height, SLA, LOV, and LAI affect the level of interception so that it has implications for photosynthetic efficiency and P-SECE at the Vegetative phase (Figure 7). Meanwhile, P-SECE during the generative stage was related to LAI, SLA, chlorophyll content, plant height, NAR, and f. This suggests that morpho-physiological changes in maize varieties fertilized with INM-based Si have a positive impact on the level of light interception, thereby increasing photosynthetic efficiency, which has implications for increasing P-SECE and plant growth in the form of plant dry weight.

However, the research carried out in one season leaves many interesting research questions for future, namely the level of interception, RUE, and growth of corn applied with Si-based INM only increased in the vegetative phase and did not differ from conventional in generative. for this reason, an evaluation is needed regarding the comparison of the amount, variant, and timing of organic and inorganic fertilisation so as to obtain a standard fertilisation that can increase RUE, growth, and yield of corn.

***Conclusion*:** The fertilization method with INM combined with Si has a positive effect on the morpho-physiology of corn plants in the vegetative phase so that the canopy architecture is more optimal for distributing solar light as shown by an increase in interception efficiency. Morpho-physiological changes are related to the level of Si uptake and the balance of macro-nutrients in plant tissues resulting in increased results and efficiency of photo-synthesis, CGR, NAR, and plant dry weight as well as P-SECE which are indicators of increased plant growth and yield. Meanwhile, in the generative phase, Si and conventional fertilization methods were significantly higher for CGR, NAR, and dry weight even though conventional P-SECE towards harvest was the lowest

compared to other treatments. P5027 Variety has a more favorable canopy architecture that is more efficient in capturing solar light than Lamuru, but the variety's P-SECE showed no significant difference with Lamuru being relatively higher during the vegetative stage and P5027 tending to be higher near harvest.

***Authors contributions statement*:** M.I. Wahyudi, designed, completed the experiment and data analysis as well as prepared the draft; A. Suryanto, Y. Sugito, A.N. Sugiharto, A. hamid, designed and finalized the draft

***Conflict of interest*:** The authors declare no conflict of interest

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***Availability of data and material*:** We declare that the submitted manuscript is our work, which has not been published before and is not currently being considered for publication elsewhere

***Code availability*:** Not applicable

***Consent to participate*:** All authors participated in this research study.

***Consent for publication*:** All authors submitted consent to publish this research. article in JGIAS.

***SDG's Addressed*:** Zero Hunger.

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